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MINIMAL REPRESENTATION AND DECISION MAKING FOR NETWORKED AUTONOMOUS AGENTS

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Final Report

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This project addresses fundamental issues that arise in information representation architectures for autonomous reasoning and learning, decentralized planning, and decision-making in multiagent systems. The overall goal of the project is to develop efficient and adaptive strategies to process, represent, exchange, and act upon relevant information from massive data collections, much of which can be irrelevant, imprecise, and contradictory. Within this context we develop results in an array of relevant topics. These include the characterization of the minimum amount of information required by a team of networked agents to solve a geometric task and the minimal number of agents required, the accurate state estimation for agent synchronization, the resilient coordination in the presence of uncertainty and failures, and the multiobjective coordination for safe operation.

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Minimal Representation and Decision Making for Networked Autonomous Agents

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Final Report

This project addresses fundamental issues that arise in information representation architectures for autonomous reasoning and learning, decentralized planning, and decision-making in multiagent systems. The overall goal of the project is to develop efficient and adaptive strategies to process, represent, exchange, and act upon relevant information from massive data collections, much of which can be irrelevant, imprecise, and contradictory. Within this context we develop results in an array of relevant topics.

Minimal Information

First, we consider what the minimum amount of information required by a team of networked agents to solve a geometric task is. This notion of minimality is abstracted through the use of set-valued sensors, and the question then becomes what assumptions need to be made on these sensor models. In fact, the set-valued sensor provides a general model of a noisy sensor since different kinds of uncertainties can be explored by imposing constraints on the kinds of sets that are returned by the sensor. As a first stab at this, the two-agent rendezvous problem is considered where one agent (the target) is equipped with no sensors and is stationary, while the other is equipped with a set-valued sensor. The set-valued conditions under which rendezvous is possible has been characterized in terms of the sensor characteristics. As part of the search for the minimum information required for a team of agents to solve a particular task, we asked the dual question: Given a certain information exchange structure, what tasks are fundamentally solvable in a distributed manner? This question was answered through necessary and sufficient conditions on the set of tasks in but unfortunately this result was not constructive in that we could not actually generate the distributed decision-making algorithms. However, a computational framework for achieving this was obtained and we now have the tools to solve distributed tasks in a systematic manner given very limited information.

Minimal Number of Agents

Second, we study the situation where we need to deploy a fleet of possibly heterogeneous autonomous agents (personnel, vehicles, robots, and so on) to service an equal number of targets while the agents consume the least amount of energy, captured by the total distance traveled by all agents. For agents with limited sensing and communication capabilities, we give a formula that computes the number of agents needed for ensuring true optimality with a high probability guarantee. When the number of agents cannot be chosen and agents have limited communication, we provide hierarchical strategies that achieve constant ratio approximation to the true optimal distance. This work is relevant to a multi-vehicle version of the Travelling Salesman Problem (TSP). We further provided a direct formula for computing the number of robots sufficient for probabilistically guaranteeing such an O(1) optimal solution with sensing and communication limitations.

State Estimation and Synchronization

We develop a Bayesian consensus filtering framework that can incorporate nonlinear target dynamic models, non-Gaussian uncertainties, and higher–order moments of the locally estimated probability distribution of the target's states. We show that combining probability distributions using a logarithmic opinion pool minimizes the sum of Kullback–Leibler divergences between the consensual estimate and each of the individual estimated probability distributions. Rigorous stability and convergence results for the proposed BCF algorithm with single or multiple consensus loops are developed. A new adaptive formation control method is developed for a large number of spacecraft or robots moving on adaptive network topologies. The adaptive graph Laplacian, introduced first in this paper, is integrated with a phase synchronization controller that synchronizes the relative motions of Euler-Lagrangian systems moving in elliptical orbits, thereby yielding a smaller synchronization error than an uncoupled tracking control law in the presence of bounded disturbances and modeling errors. Furthermore, we present a connection among contraction theory using a Riemannian metric, input-to-state stability (ISS), output passivity, and finite-gain Lp stability, which are common tools for analyzing networked nonlinear systems.

Resilient Coordination

We have considered distributed coordination algorithms that are resilient to possible robot failures for multi-robot systems. These include random failures experienced by individual robots, as well as the possibility of malicious behavior by some of the robots. We have specifically addressed the problems of rendezvous and deployment (i.e., coverage control) among the coordination tasks. We considered the performance of distributed control algorithms for networked robotic systems when one or more robots fail to execute the optimal policy We provided an optimization algorithm based on finite-horizon dynamic programming, and obtained solutions through numerical simulation. Our results showed that in general adversarial nodes are able not only to impede convergence toward consensus, but can also affect global changes in the topology of the communication graph for the cooperative agents. We considered the problem of designing distributed control algorithms to solve the rendezvous problem for multi-robot systems with limited sensing for situations in which random nodes may fail during execution. We considered the problem of worst-case performance by a mobile sensor network (MSN) when some of the nodes in the network fail. We posed the problem as a multi-stage decision process, and used forward dynamic programming over a finite horizon to numerically compute optimal strategies for the adversaries. We presented a distributed robust deployment algorithm for optimal coverage by a mobile sensor network (MSN). We introduced a distributed algorithm for our optimal sensor placement problem that requires only simple peer-to-peer (P2P) communications. We showed via simulation results that our algorithm converges in finite time, and provides competitive coverage performance in the presence of individual node failures.

Multi-objective Coordination

We considered the problem of multi-agent coordination and control under multiple objectives, and presented a set-theoretic formulation amenable to Lyapunov-based analysis and control design. A novel class of Lyapunov-like barrier functions is introduced and used to encode multiple, non-trivial control objectives, such as collision avoidance, proximity maintenance and convergence to desired destinations. The construction is based on recentered barrier functions and on maximum approximation functions. Thus, a single Lyapunov-like function is used to encode the constrained set of each agent, yielding simple, gradient-based control solutions. The derived control strategies are distributed, i.e., based on information locally available to each agent, which is dictated by sensing and communication limitations. Furthermore, the proposed coordination protocol dictates semi-cooperative conflict resolution among agents, which can be also thought as prioritization, as well as conflict resolution with respect to an agent (the leader) which is not actively participating in collision avoidance, except when necessary. The considered scenario is pertinent to surveillance tasks and involves nonholonomic vehicles. Within this framework we also considered the problem of dynamic coverage control for a team of nonholonomic agents. The novelties of the approach rely on the consideration of anisotropic sensing, which is realized via conic sensing footprints, a new form of sensing (coverage) functions for each agent, and on a new form of avoidance functions. The proposed approach is suitable for surveillance applications where each agent is assigned with the task to gather enough information (such as video streaming) in an obstacle environment. The efficacy of the approach is demonstrated through simulation results.

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Abstract

This project addresses fundamental issues that arise in information representation architectures for autonomous reasoning and learning, decentralized planning, and decision-making in multiagent systems. The overall goal of the project is to develop efficient and adaptive strategies to process, represent, exchange, and act upon relevant information from massive data collections, much of which can be irrelevant, imprecise, and contradictory. Within this context we develop results in an array of relevant topics. These include the characterization of the minimum amount of information required by a team of networked agents to solve a geometric task and the minimal number of agents required, the accurate state estimation for agent synchronization, the resilient coordination in the presence of uncertainty and failures, and the multiobjective coordination for safe operation.

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Archival Publications (published) during reporting period:

1. J. Yu, S.-J. Chung, and P. G. Voulgaris, “Target Assignment in Robotic Networks: Distance Optimality Guarantees and Hierarchical Strategies,” IEEE Transactions on Automatic Control, vol. 60, no. 2, February 2015, pp. 327-341.

2. S.-J. Chung, S. Bandyopadhyay, I. Chang, and F. Y. Hadaegh, “Phase Synchronization Control of Complex Networks of Lagrangian Systems on Adaptive Digraphs,” Automatica, vol. 49, no. 5, May 2013, pp. 1148-1161.

3. S. Bandyopadhyay, S.-J. Chung, F. Y. Hadaegh, “Probabilistic Guidance of Swarms using Optimal Transport,” IEEE Multi-conference on Systems and Control (MSC), Antibes, France, Oct. 8-10, 2014.

4. D. Morgan, G. P. Subramanian, S. Bandyopadhyay, S.-J. Chung, F. Y. Hadaegh, “Probabilistic Guidance of Distributed Systems using Sequential Convex Programming,” IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Chicago, Illinois, Sept. 14–18, 2014, pp. 3850-3857.

5. J. Yu, S.-J. Chung, and P. G. Voulgaris, “Distance Optimal Target Assignment in Robotic Networks under Communication and Sensing Constraints,” IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, China, 2014, pp. 1098-1105. (PDF)

6. J. Yu, S.-J. Chung, and P. G. Voulgaris, “Traveled Distance Minimization and Hierarchical Strategies for Robotic Networks,” 2014 International Symposium on Communications, Control, and Signal Processing, Special Session on Modeling and Control of Complex Networks, May 22-23, Athens, Greece, 2014, pp. 491-496. Invited paper.

7. S. Bandyopadhyay and S.-J. Chung, “Distributed Estimation using Bayesian Consensus Filtering,” American Control Conference (ACC), Portland, Oregon, June 4-6 2014, pp. 634-641.

8. S. Bandyopadhyay, S.-J. Chung, and F. Y. Hadaegh, “Inhomogeneous Markov Chain Approach to Probabilistic Swarm Guidance Algorithm,” 5th Int. Conf. on Spacecraft Formation Flying Missions and Technologies (SFFMT), Munich, Germany, May 2013.

9. Z. Costello and M. Egerstedt. The Degree of Nonholonomy in Distributed Computations. IEEE Conference on Decision and Control, Los Angeles, CA, Dec. 2014.

10. Z. Costello and M. Egerstedt. From Global, Finite-Time, Linear Computations to Local, Edge-Based Interaction Rules. IEEE Transactions on Automatic Control. Accepted for publication. To appear 2015.

11. Z. Costello, J. Ruths, and M. Egerstedt. On the Construction of Local Interaction Rules that Perform Global Linear Computations. IEEE Conference and Decision and Control, 2015. Submitted.

12. H. Park, S. Hutchinson, "A Distributed Optimal Strategy for Rendezvous of Multi-Robots with Random

Node Failures," Proc. IEEE/RSJ Int'l Conf. on Intelligent Robots and Systems, 2014, pp. 1155-1160.

13. H. Park, S. Hutchinson, "Robust Optimal Deployment in Mobile Sensor Networks with Peer-to-Peer Communication," Proc. IEEE Int'l. Conf. on Robotics and Automation, 2014, pp. 2144-2149.

14. H. Park, S. Hutchinson, \Worst-Case Performance of a Mobile Sensor Network Under Individual Sensor Failure," Proc. IEEE Int'l. Conf. on Robotics and Automation, pp. 895-900, 2013.

15. H. Park, S. Hutchinson, \Worst-Case Performance of Rendezvous Networks in the Presence of Adversarial Nodes," Proc. IEEE/RSJ Int'l Conf. on Intelligent Robots and Systems, pp. 5579-5585, 2013.

16. D. Panagou, D.M. Stipanovic and P.G. Voulgaris, Distributed coordination control for multi-robot networks using Lyapunov-like barrier functions, accepted in IEEE TAC.

17. D. Panagou, D.M. Stipanovic and P.G. Voulgaris, Dynamic coverage control in unicycle multi-robot networks under anisotropic sensing, accepted in Frontiers in Robotics and AI.

18. M. Naghnaeian and P. G. Voulgaris, Performance optimization over positive l-inf cones, American Control Conference, 2014.

19. G.M. Atinc, D.M. Stipanovic, P.G. Voulgaris and M. Karkoub, Swarm-based dynamic coverage control, 53rd IEEE Conference on Decision and Control, 2014.

20. D. Panagou, D.M. Stipanovic and P.G. Voulgaris. Vision-based dynamic coverage control for nonholonomic agents, 53rd IEEE Conference on Decision and Control, 2014.

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